ERDC/CHL CETN-IV-29
September 2000

US Army Corps of Engineers®

Circulation Patterns at Tidal Inlets with Jetties

by Adele Militello and Steven A. Hughes

PURPOSE: This Coastal Engineering Technical Note (CETN) provides guidance on interpreting horizontal circulation patterns at inlets.

BACKGROUND: Tidal inlets provide a conduit for water exchange between the ocean and coastal bays, lagoons, and estuaries. They also serve as navigation routes for commercial and recreational vessels. The U.S. Army Corps of Engineers maintains Federal inlets on all coasts of the United States and its territories. The Corps manages inlets primarily by construction of jetties and by dredging. Jetties stabilize the entrance and the entrance channel, and they also protect vessels from waves as they travel between the surf zone and deep water.

Tools for inlet management have become more sophisticated in recent years with advances in field instrumentation and computing capabilities. These improvements have yielded high-quality data and detailed calculations of inlet currents. Engineering problems that can benefit from interpretation and understanding of circulation patterns at inlets are prediction and prevention of scour, channel migration, and navigation safety.

Circulation patterns are specific to each inlet, but certain properties are common to many inlets. Common properties include ebb or flood dominance, preferred channels on ebb and flood tide, eddy formation and migration, and jetty control on flow patterns. This CETN describes the circulation patterns and related processes common to many inlets with focus on those with dual jetties. Circulation patterns described herein assume that the tide is the sole or dominant forcing.

INLET CIRCULATION: Inlet circulation is governed by tide range, bay geometry, inlet geometry, presence and configuration of structures, bottom topography, and nontidal forcing, such as wind and river inflow. The rise and fall of the ocean tide is the primary forcing. Inlet currents are strong with typical maximum speed in mainland U.S. Atlantic inlets being about 1 to 2 m/s. Representative circulation patterns and morphological features at inlets are shown in Figure 1. Flood currents form channels on both sides of the inlet entrance. As water traverses the inlet and enters the bay, the current is primarily aligned with the inlet and flows over the flood shoal where the velocity is reduced and material is deposited. This process forms a flood ramp, which is the sloped front face of the flood shoal. During ebb tide, the primary conduits of water are channels located between the flood shoal and the barrier island. These ebb channels merge at the inlet forming a main ebb channel. Strong ebb currents exiting the inlet form a jet (Joshi 1982; Joshi and Taylor 1983; Mehta and Joshi 1988). As the jet exits the inlet, it expands and loses velocity, depositing material onto the ebb shoal.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **SEP 2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Circulation Patterns at Tidal Inlets with Jetties (EDC/CHL CHETN-IV-29)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Militello, Adele, and Hughes, Steven A.**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
This Coastal Engineering Technical Note (CHETN) provides guidance on interpreting horizontal circulation patterns at inlets.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

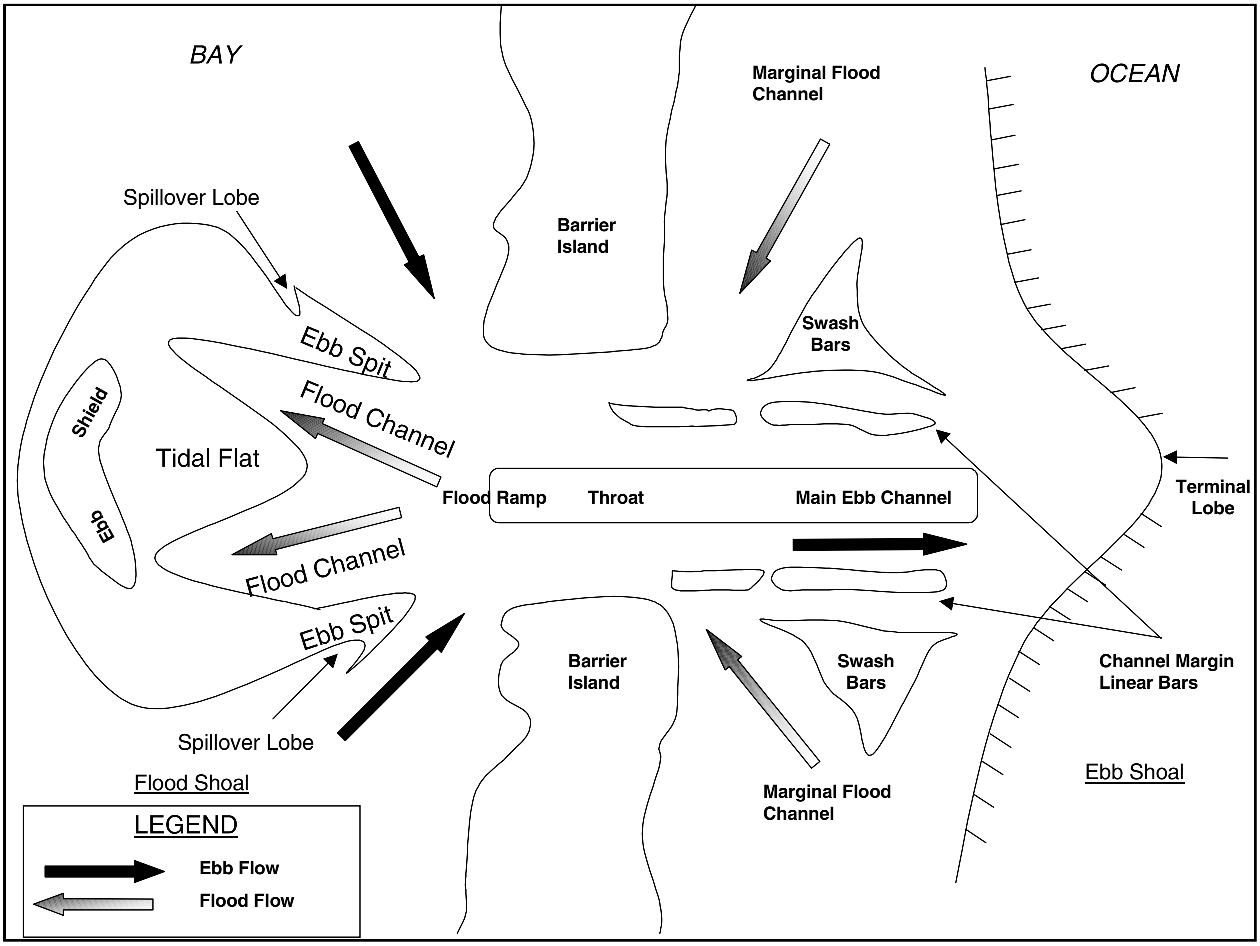


Figure 1. Typical inlet flow patterns and morphological features (Hayes 1975).

The described pattern of flood and ebb circulation is common, but every inlet has unique patterns owing to the local situation. For example, the main ebb channel may be in the center of the inlet or along one side. Factors that control the local circulation include inlet geometry, tide range, bay-channel orientation, distribution of discharge through channels, wave climate, number and configuration of jetties, and dredging activity.

FLOOD AND EBB DOMINANCE: Asymmetry of the tidal current means the average peak flood or ebb current is stronger than its opposing current (flood stronger than ebb or ebb stronger than flood). Tidal asymmetry is common in inlets. The asymmetry is called "flood dominant" if the flood current is stronger than the ebb current, and "ebb dominant" if the ebb current is stronger than the flood current. An example of an ebb-dominant current is shown in Figure 2. Note that convention defines flood current as positive and ebb current as negative. Peak ebb current is 1.15 m/s and peak flood current is 0.97 m/s. In an inlet and bay system in which no tributary input or other significant nontidal forcing is present, the net discharge is zero through the inlet, even though there is asymmetry in the tidal current.

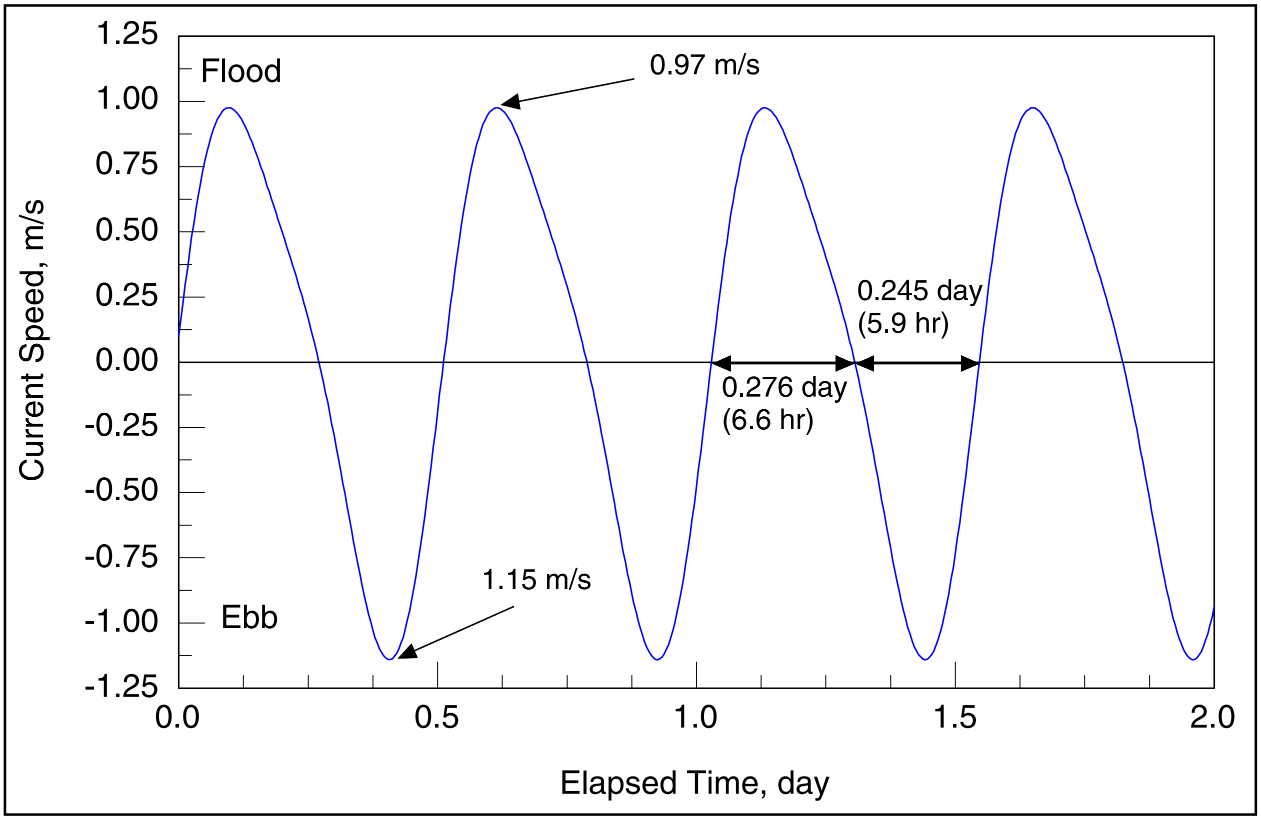


Figure 2. Ebb-dominated current formed by 30 deg lead of the M_2 over the M_4 tidal constituent

How can the net discharge be zero if the current is stronger on the ebb or flood tide? There are two properties that control the relationship between discharge and tidal current. One is the shape of the velocity curve, and the other is the difference in tidal phase between the water level and current. The shape of the velocity curve depends on friction, bathymetry and channel geometry, and nonlinear interactions within the water motion and is described by the relative phases between tidal constituents. (For detailed discussion on tidal constituents, see Defant 1961; Dronkers 1964; Scheffner 1994, 1995.) Phase relationships between tidal constituents describe whether the tidal curves are flood dominant, ebb dominant, or have no dominance (Aubrey and Speer 1985; DiLorenzo 1988), in the absence of significant nontidal forcing. As an example, consider an M_2 (semidiurnal, 12.42-hr period) tidal current and its first harmonic the M_4 (quarter-diurnal, 6.21-hr period) having amplitudes of 1.0 and 0.1 m/s, respectively. The phase relationship between the M_2 and M_4 components is described as

$$\theta = 2\phi_{M2} - \phi_{M4} \tag{1}$$

where θ is the phase difference between the two constituents, ϕ_{M2} is the phase of the M_2 constituent, and ϕ_{M4} is the phase of the M_4 constituent. This phase relationship holds because the frequency of the M_4 constituent is twice that of the M_2. If the M_4 tide lags the M_2 tide by 30 deg, the combined tidal current has the ebb-dominated shape shown in Figure 2. The duration of the flood tidal current (6.6 hr) exceeds that of the ebb tidal current (5.9 hr). The greater peak ebb speed balances the longer flood duration such that there is a zero mean velocity through the inlet.

Some inlets exhibit tidal currents in which the mean velocity through the inlet is not zero, yet the net discharge over a tidal cycle is zero. This situation occurs if the tidal curve for water level is not in phase with that for the current through the inlet. Because discharge is a function of water level and current, the phase difference between the two variables creates a time-varying discharge that has a net value of zero over a tidal cycle.

As an example, water level plotted to mean tide level (mtl), current speed, and discharge tidal curves for a flood-dominated inlet are shown in Figure 3. The mean current speed is –0.1 m/s (ebb-directed) owing to the longer duration of ebb current. Peak tidal current precedes peak water level by 2.5 hr (0.105 day). When the current switches from flood to ebb, the water level is near its peak flood value. Maximum ebb current coincides with lower water level. Flood current commences during lower water level and peak current occurs during higher water level. Peak discharge is greater during the strong flooding current because the water level is higher than during peak ebb current (peak ebb and flood velocities are nearly equal). Although the ebb discharge is smaller than the flood, it has longer duration. Thus, the phase difference between water level and current combined with the asymmetrical tide produces a discharge curve that balances flood and ebb, giving a zero net discharge.

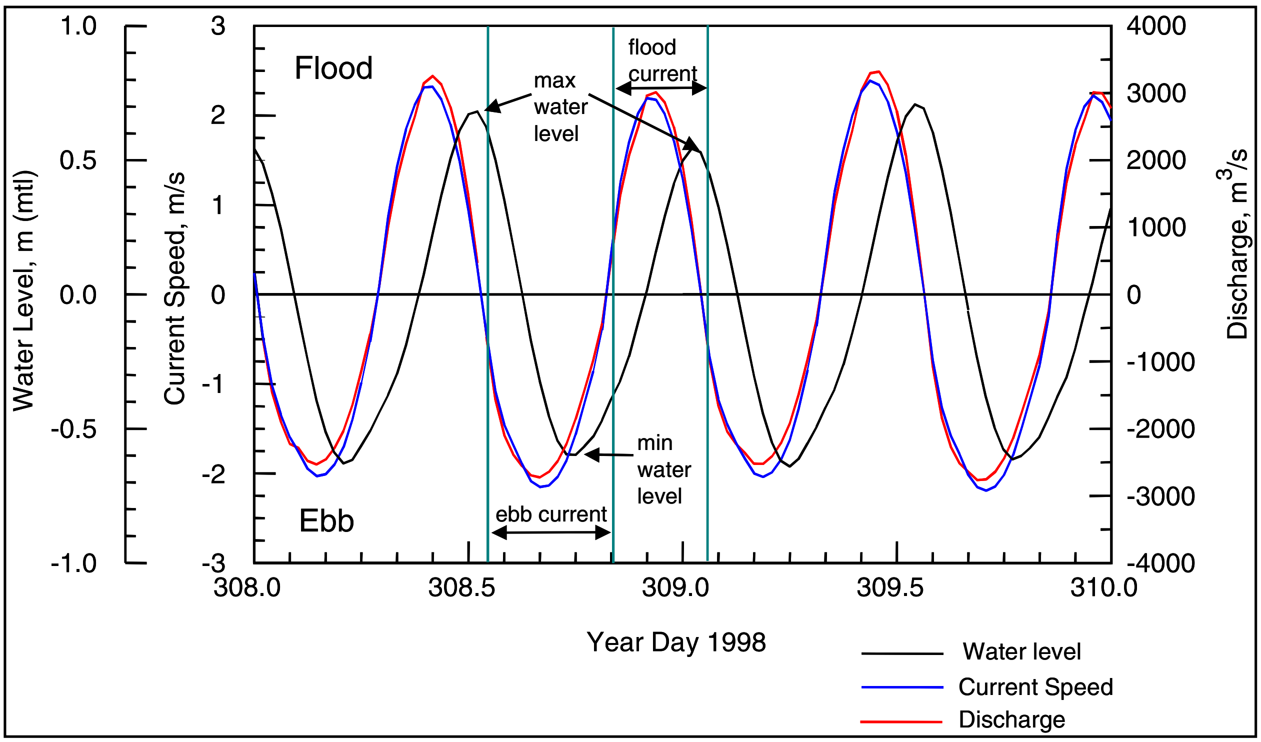


Figure 3. Example relationship between water level, current speed, and discharge at a flood-dominated inlet

Ebb and flood dominance can play a role in preferred sand transport direction at tidal inlets. The bias in peak velocity creates a difference in the amount of material being transported on flood and ebb tides. For example, a flood-dominated inlet may transport sand into bay channels and can also create multiple flood shoals (FitzGerald 1988).

FLOOD AND EBB CHANNELS: Inlets often possess two channels, with one channel favoring flood flow and the other favoring ebb. These channels are formed by strong currents that occupy particular locations as dictated by the local hydrodynamics. Controls on channel location are inlet orientation, structures, and channels leading into the inlet from the bay. Figure 1 shows flood and ebb channels for a typical inlet. In this figure, the main ebb channel is located in the center of the inlet and the flood channels are along the inlet margins. At Ponce de Leon Inlet, FL, the ebb current is strongest along the side of the channel adjacent to the north jetty, as shown in Figure 4. Scour near the north jetty at Ponce de Leon Inlet may be the result of the strong ebb current (Militello and Zarillo 2000).

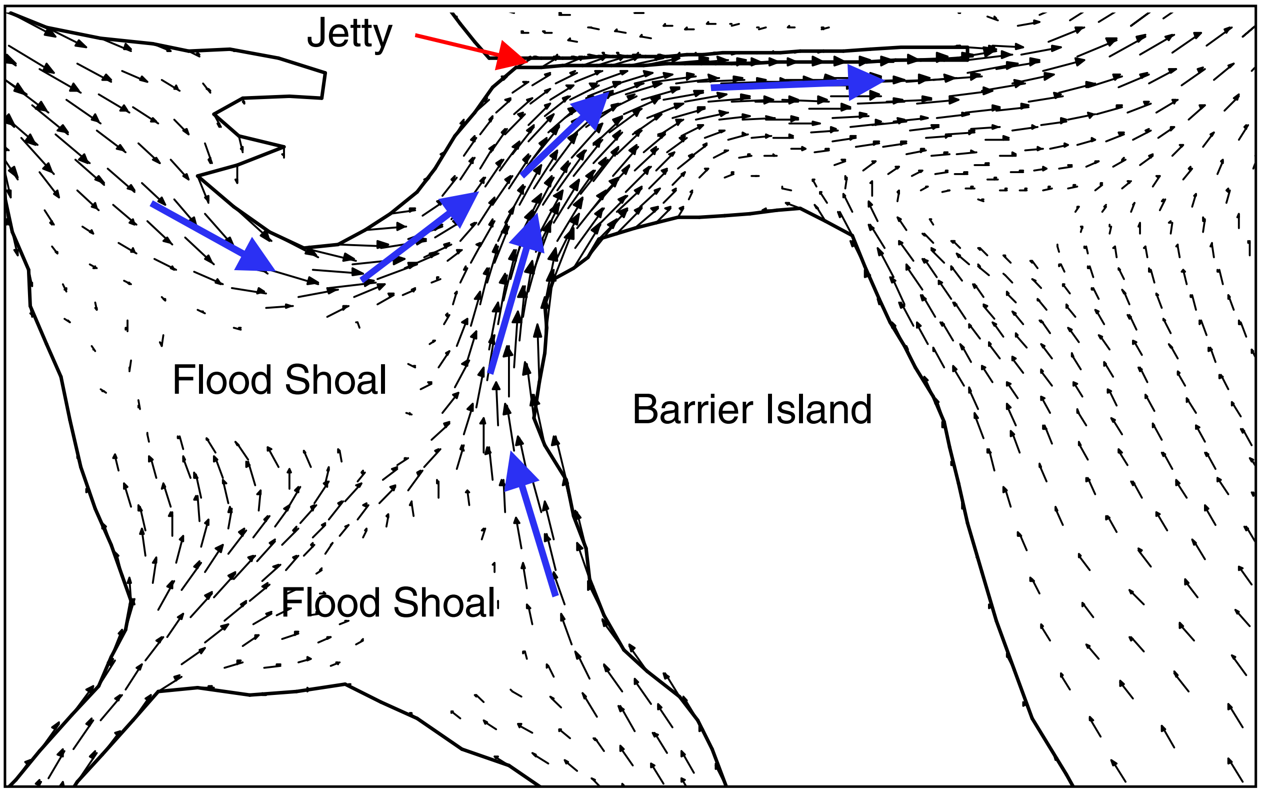


Figure 4. Ebb current at Ponce de Leon Inlet, FL

Scour can occur by an ebb current that impinges on a jetty (Hughes 1997), as illustrated in Figure 5. As the ebb current is deflected by the jetty, the directional change in momentum narrows the flow streamlines, accelerating flow along the jetty. The increased current speed scours the bottom adjacent to the jetty toe, and sediment deposition occurs in the center of the entrance channel where the current has decreased magnitude. Over time the deeper, more navigable portion of the channel migrates closer to the jetty. Ebb currents can also be modified by any type of flow constriction created by jetty or shoreline revetment alignment.

During flood tide, some inlets may experience flow separation at the seaward ends of the jetties that tends to direct flow along a preferred path through the inlet throat. Flow separation often generates vortex-like rotational flows that may be strong enough to disrupt small-craft navigation. Discussion of jetty geometry control on flow patterns is given next.

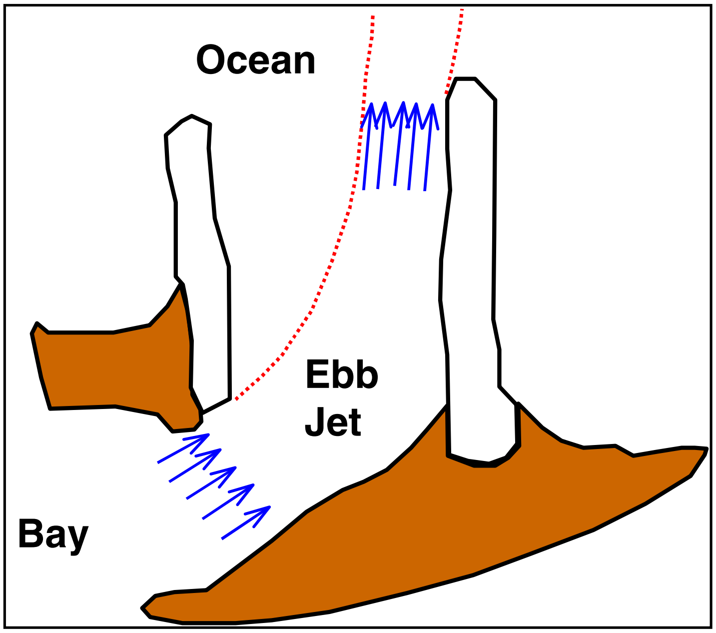
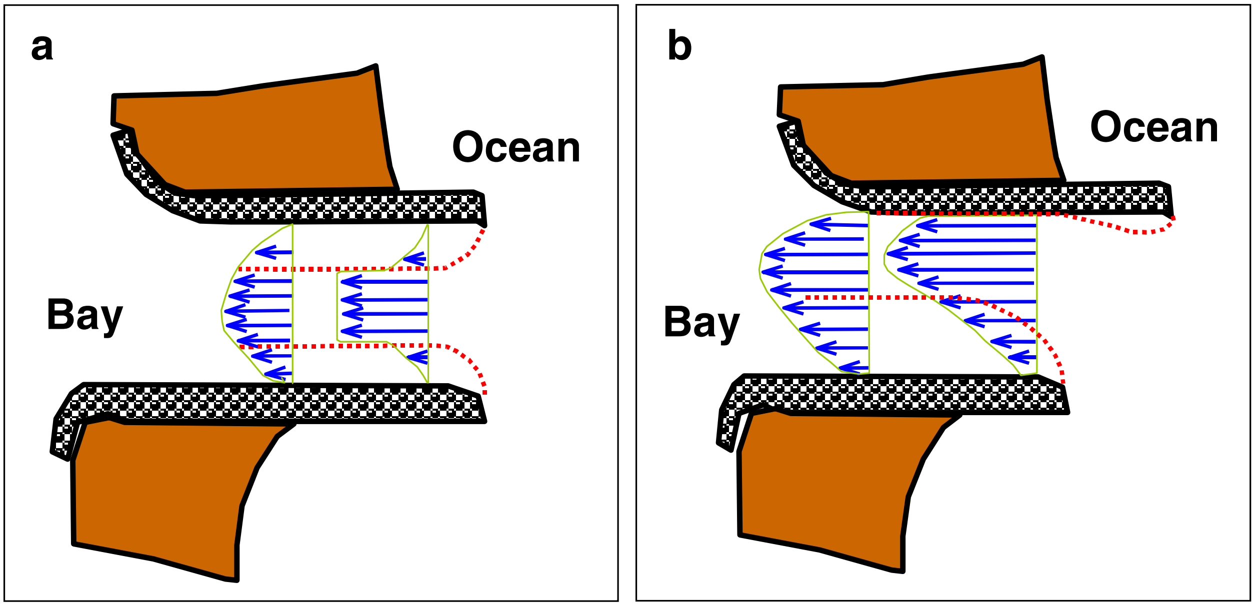


Figure 5. Redirection of ebb flow by jetty

JETTY CONTROL ON FLOW PATTERNS: The presence and configuration of jetties at inlets plays a significant role in controlling the circulation pattern. Patterns of current flow within inlets are different for equal-length and offset parallel jetties, as shown in Hughes (2000). Equal-length jetties require water to enter the inlet at the same distance offshore, preventing bias of the current on one side of the inlet as schematically shown in Figure 6a. Flow separation at the jetty tips is approximately distributed equally on each side of the inlet. This distribution directs the current along the channel center line. Thus, near the jetty tips, the central portion of the inlet carries the strongest current with strength weakening laterally toward the jetties. Further into the inlet, flow entrainment by the flood jet decreases current speed in the center of the channel and spreads the flow distribution across the channel. Thus, distribution of the current speed in the interior of the inlet is broadened as compared to that near the inlet entrance.

Offset jetties create a bias in the current in which water with the greatest speed enters the inlet from the side with the shorter jetty, as shown in Figure 6b. The current is then directed at an angle to the inlet center line. This situation results in the strongest current being near the shorter jetty on the outer portion of the inlet, and shifting to the other side in the central portion of the inlet.

EBB JET AND EDDIES: Jet flows at inlets extend from the interior of the inlet to some distance seaward, depending on the strength of the current. The presence of jetties enhances the jet by constraining the flow. Jet orientation is initiated parallel to the jetties, but that orientation can change through the ebb cycle. Steep velocity gradients occur if jetties are present and these gradients are located within and parallel to the jet as well as perpendicular to it. Because of these velocity gradients, the jet is enhanced and eddies are formed. In particular, jetty tips are points where velocity gradients perpendicular to the jet flow are strong. Eddy formation initiates near jetty tips, but eddies can migrate with lengthening of the jet and changes in ocean tidal current. Shinnecock Inlet, NY, serves as an example of ebb jet and eddy patterns at jettied inlets.



a. offset jetties b. parallel jetties

Figure 6. Flood flow distribution for equal-length jetties

At Shinnecock Inlet migration of an ebb eddy reorients the ebb jet (Militello and Kraus 2000). This reorientation, occurring twice per day, exerts control on the location of the entrance channel. The process of jet and eddy formation and migration, calculated by a numerical circulation model, is shown in 1-hr intervals in Figure 7. As the ebb cycle begins, a small eddy east of the east jetty starts to form (Figure 7a). After 1 hr, the jet has started to form and its direction is parallel to the jetties (Figure 7b). An eddy west of the jet has formed that is smaller than the east eddy, and the east eddy has increased in size and migrated south. The east eddy and jet entrain flow from each other with momentum entering the jet from the eddy's northwest side and momentum entering the eddy on its southwest side. Coupling between the jet and east eddy result in a curvature of the jet toward the east on its seaward end. Two hours into the ebb cycle, the east eddy has grown and migrated south and slightly west (Figure 7c). The west eddy has grown in size, but has remained stationary. The jet has rotated toward the southwest, but its seaward tip still curves toward the southeast. Realignment of the jet occurs from the east eddy pushing the jet westward as it migrates. Three hours into the ebb cycle, the east eddy has migrated further toward the southwest, pushed the jet tip westward (Figure 7d). A third eddy has formed west of the jet so that the jet tip is pinched between two eddies. The west eddy has remained stationary and has not changed size. At this time, the jet is at its maximum strength and overlies the channel.

The entrance channel to Shinnecock Inlet is dredged in an alignment parallel to the jetties. Over time, the channel has migrated westward. Realignment of the jet by the ebb eddies is a significant factor in the movement of the channel. Other inlets experience similar ebb current patterns, and local ebb tidal processes can be one major control of the entrance channel alignment.

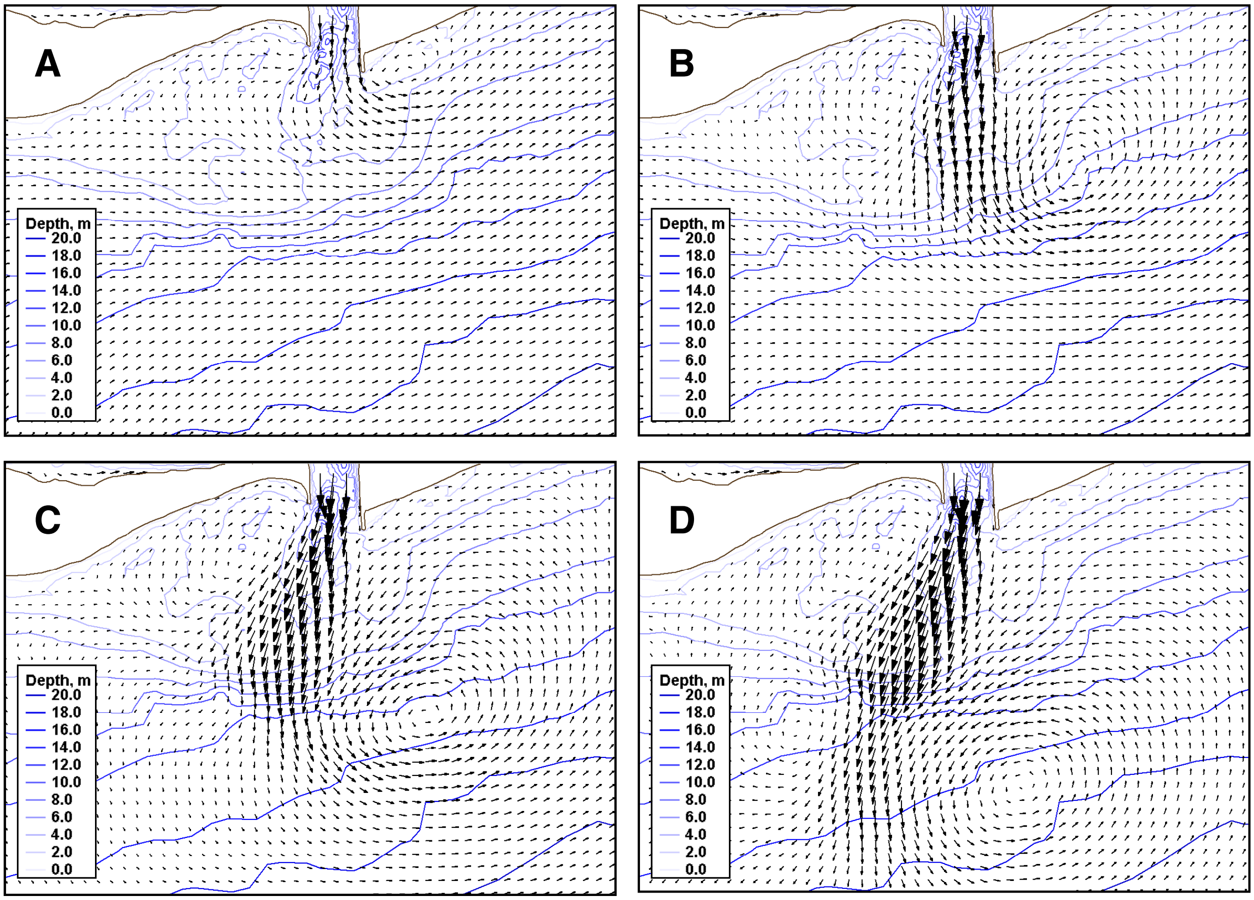


Figure 7. Jet and eddy formation and migration at Shinnecock Inlet, NY, offset jetties

For equal-length jetties, the process of jet and eddy formation occurs, but the patterns are modified as compared to offset jetties. To illustrate the differences, Figure 8 shows calculated vector plots at Shinnecock Inlet with the west jetty lengthened to the same distance offshore as the east jetty. Comparison snapshots correspond to the same times as in Figure 7. Figure 8a shows the beginning of the ebb tidal cycle. At this time, flow curvature appears at the jetty tips, but eddies have not formed yet. After one hour (Figure 8b), the jet and eddy formation is similar to that with the offset jetties (Figure 7b). However, close inspection reveals that the center of the eddy west of the west jetty is further seaward with the equal-length jetties as compared to the offset jetties. The circulation patterns two hours into the ebb cycle are shown in (Figure 8c). The jet is narrower than with the offset jetties and the center of the west eddy is further seaward. Thus, the lengthened west jetty allows for propagation of the west eddy further offshore, which constrains the rotation and width of the ebb jet. By the third hour of ebb flow (Figure 8d), the third eddy west of the jet has formed. The eddy is located southeast of the similar eddy that forms for the offset jetties. The jet is constrained on its east and west sides by eddies that are at an equal distance seaward. This situation keeps the jet nearly parallel to the inlet. Because the jet exerts control over the location of the navigation channel, self-scouring of the channel would tend to occur parallel to the inlet with equal-length jetties. Offset jetties provide a pivot point that allows the jet to swing during the ebb tide, displacing the location of the entrance channel from straight.

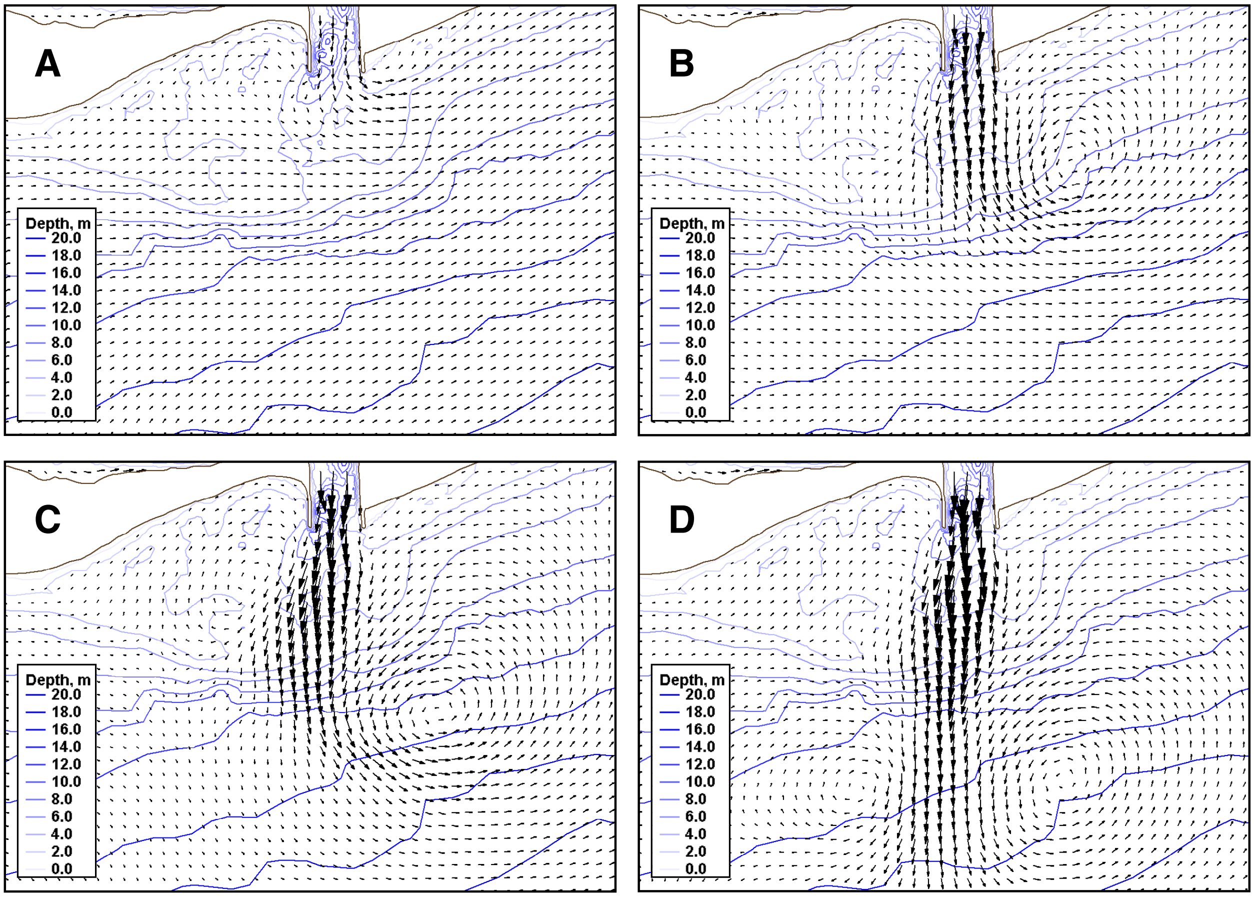


Figure 8. Jet and eddy formation and migration at Shinnecock Inlet, NY, equal-length jetties

DISCUSSION: This CETN has described general horizontal circulation patterns common to most inlets. These patterns will vary according to the geomorphology, dredging practice, jetty alignment, and tidal forcing, among other factors, at the particular inlet.

It has been shown that the horizontal circulation is often known or can be predicted with sufficient accuracy to reduce or mitigate scour, improve channel alignment, and qualitatively predict sedimentation patterns. Such predictions can be performed in numerical models (Militello 1998) and physical models (Seabergh 1999).

ADDITIONAL INFORMATION: Questions about this Technical Note can be addressed to Dr. Adele Militello at (601) 634-3099 and email at *militea@wes.army.mil* or to Dr. Steven A. Hughes at (601) 634-2026 and email at *hughess@wes.army.mil*. For information about the Coastal Inlets Research Program, please contact the Program Technical Leader, Dr. Nicholas C. Kraus, at (601) 634-2016 or email at krausn@wes.army.mil. This technical note should be cited as follows:

> Militello, A., and Hughes, S. A. (2000). "Circulation patterns at tidal inlets with jetties," ERDC/CHL CETN-IV-29, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

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